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The effect of nanofibrous membrane thickness on fracture behaviour of modified composite laminates – A numerical and experimental study

H. Saghafi [a, *], S.R. Ghaffarian [a, **], T.M. Brugo [b], G. Minak [b], A. Zucchelli [b], H.A. Saghafi [c]

[a] Department of Polymer Engineering and Color Technology, Amirkabir University of Technology, Hafez Ave. 424, Tehran 15914, Iran
[b] Dipartimento di Ingegneria Industriale, Alma Mater Studiorum-Università di Bologna, Viale Risorgimento 2, Bologna 40125, Italy
[c] Department of Mechanical Engineering, Tarbiat Modares University, Tehran 14115-143, Iran

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ABSTRACT

Delamination is the most frequent failure mode in laminated composite materials and it may cause catastrophic failure in critical engineering structures. One of the most popular ways to prevent this failure is toughening the matrix. Recently, it has been proved that polyvinylidene fluoride (PVDF) nanofibers have the potential to increase the fracture toughness of epoxy-based composites. Therefore, in this study, the influence of PVDF-membrane thickness on mode-I fracture toughness of interleaved CFRP laminates is considered using experimental and numerical methods. For experimental investigation, the fracture behavior of interleaved laminates has been determined by Double Cantilever Beam (DCB) tests using two different thicknesses of membrane. On the other hand, finite element method (cohesive elements) is used for numerical considerations of fracture behavior during mode-I loading. The results show that thin and thick nanofibrous mat leads to 42% and 98% enhancement in mode-I fracture toughness, respectively. It is also shown that bi-linear traction-separation law is a suitable method to model PVDF-modified laminate under mode-I loading. By finding the three cohesive parameters K°, G_{I}, σ_{max}, and repeating the study for mode-II, it is possible to predict the behavior of nanomodified laminates under other loading conditions.

1. Introduction

The employment of polymeric composite laminates in vary industries such as aerospace, automotive, and sporting goods, has increased significantly over the last decade, due to increasing requirements in terms of stability and durability of materials, and at the same time, a reduction of the cost of maintenance, operation and manufacturing. Because of the following properties of thermoset polymers, they are used mostly as matrix for composite laminates: 1- being liquid at room temperature 2- resistance to heat and high temperature 3- excellent adhesion 4- excellent resistance to solvents and corrosives. On the downside, their high inherent brittleness restricts the number of possible application, which may cause, for laminate materials, delamination even under very low velocity impact [1,2].

Up to now, various methods have been introduced to prevent delamination in composite materials such as stitching [3,4], braiding [5] and Z-pinning [6]. Although these methods are useful to prevent delamination, they usually cause a reduction of the in-place mechanical properties [7]. Since most thermoplastic polymers are tougher than thermoset polymers [8], it was suggested to apply a film of these materials on certain interlayers of laminate samples [9]. The efficiency of this method in increasing fracture toughness of thermoset-based composite was remarkable [10–12], but recently Dzenis and Reneker [13] proposed a new method to increase the effectiveness of these toughener. They proposed to interleave a nanofibrous membrane of thermoplastic polymers between composite layers instead of using a film of that polymer. Because of the following reasons the nanofiber form is more effective than the film form of a polymer on fracture toughness of composites: 1- extremely high porosity (for example 67% for Nylon

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* Corresponding author.
** Corresponding author.

E-mail addresses: hsaghafi@aut.ac.ir (H. Saghafi), sr_ghaffarian@aut.ac.ir (S.R. Ghaffarian).

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6,6 electrospun nanofibers [14]), 2- very large surface-to-volume ratio, and 3- excellent permeability, which allows the matrix to flow through and adequately impregnate the nanofibrous membrane. Two studies conducted by Zhang et al. [15] and Magniez et al. [16] compared the capability of both film and nanofibrous morphologies of PVDF on toughening the matrix. Interestingly [16] showed that PVDF film decreased mode-II fracture toughness of CFRP laminates about 57% while the nanofiber form improved it of approximately 57%.

Different kinds of nanofibers have been introduced and considered by researchers which have the ability to toughen epoxy-based composites, such as Polysulfone (PSF) [17], Polycaprolactone (PCL) [15,18], Nylon 6, 6.6, and 6.9 [19–24], Phenoxy [25], and PVDF [26]. Deep researches have been conducted for some of these polymers, such as Nylon, but some others, like e.g. PVDF, are still understudied. Until recently, it was believed that PVDF nanofibers could not improve mode-I fracture toughness of laminates [15,16], but Saghafi et al. [26] recently proved that it is instead possible under specific situations.

Another way for investigation the fracture response of nano-modified laminates is numerical analysis. One of the best technique for simulating the delamination between composite layers is embedding cohesive elements at the interface of plies. These elements behave according to traction-separation law in which the failure initiation is related to interfacial strength. After reaching this point, load-carrying capability of element decreases until the complete separation, which cause the element to be deleted [27]. According to the best knowledge of authors, only two studies have been published recently in which the effect of Nylon 6.6 on cohesive zone parameters is considered under mode-I and II loading using ABAQUS software [28,29]. Generally a bi-linear traction-separation law is applied for simulating mode-I and II fracture tests, but it is shown in Refs. [28,29] that because of bridging phenomena caused by Nylon 6.6 nanofibers, a tri-linear traction-separation law has to be used for modelling the delamination process.

As mentioned earlier, the research on the fracture behavior of PVDF-modified laminates is very limited. There are many factors that affect its toughening capabilities, and one of these is the thickness of the nanofibrous membrane. Therefore in this paper a numerical and experimental study were conducted on mode-I fracture toughness of CFRP laminates modified with two different thicknesses of membrane. In the experimental study, the effect of membrane thickness on energy release rate for mode-I fracture testing (G_I) was considered; scanning electron and optical microscopes were utilized for fractographical analysis in exploring the toughening mechanisms. In the numerical study, the presence of electrospun nanofibrous mat as interleaving material in composite laminate mode-I fracture tests was numerically simulated using cohesive zone method (in ABAQUS software).

2. Materials and methods

2.1. Materials

PVDF nanofibers have been manufactured by electrospinning. The polymeric solution used in the process consists of PVDF powder (Solef® 6008) purchased from Solvay and Dimethyl sulfoxide and Acetone (as solvent) provided by Sigma Aldrich.

[0/90] Carbon/epoxy prepreg (GG240T2IMP752-45% produced by Impregnatex Compositi S.r.l.) was used to manufacture the test samples. Carbon fabric is Twill 2/2240 g/smq and the applied resin is epoxy IMP752 (source: Impregnatex Compositi S.r.l.). Composite and PVDF properties are presented in Table 1 and Table 2, respectively.

Table 1
GG240T2IMP752-45% laminate properties (source: Impregnatex Compositi S.r.l.).

Property	Value
weight (gr/m^2)	435
Resin Content (%)	45 ± 3
Layer thickness (mm) (Molded with 3 bar pressure)	0.26
Flexural strength (MPa)	800
Flexural modulus (GPa)	59
Tensile strength (MPa)	600
Tensile modulus (GPa)	59
Interlaminar shear (MPa)	60

Table 2
PVDF properties (source: Solvay website).

Property	Value
Density (gr/cc)	1.78
Melting point (°C)	170
Glass transition temperature (°C)	−32
Tensile Strength, Ultimate (Mpa)	35–50
Modulus of Elasticity (Gpa)	2.5
Elongation at Break (%)	20–50

2.2. Nanofiber production

Electrospinning is a novel technique that can be used to produce nano-scaled structures with a variety of morphologies. Fiber size and distribution can be varied significantly by controlling the process parameters such as feed rate of the solution, voltage, distance between needle tip and collector, and etc. For producing nanofibers, 15% w/v PVDF powder was dissolved in a 30/70 v/v solution of Dimethyl sulfoxide (DMSO) and Acetone (30:70 v/v). A very important point to have continuous electrospinning process and thus good-quality nanofibers, is heating the solution for about 2 min at 40 °C before the electrospinning: it causes a transparency in the solution. Otherwise, because of suspended PVDF particles, the solution is completely white. The solution was then transferred to an electrospinning machine manufactured by Spinbow Company (Fig. 1).

Electrospinning parameters were as follows: applied voltage 12 kV, feed rate 0.01 mL/min, distance between the collector and

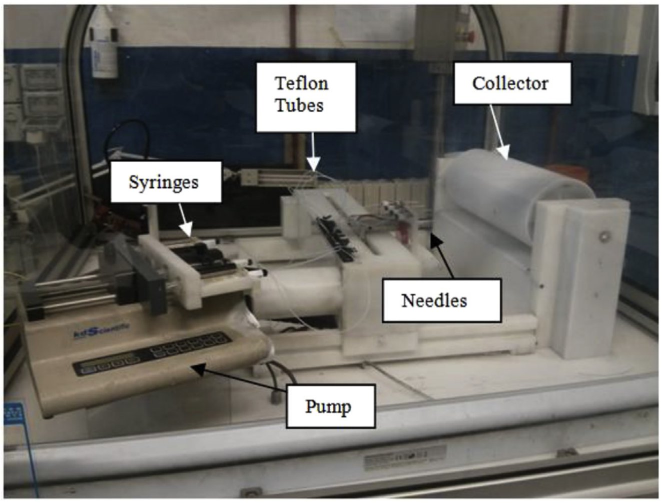

Fig. 1. Electrospinning machine for producing nanofibers.